Impact of fermionic singlets on lepton universality tests

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Neutrino oscillations

- Oscillation probability is non-zero only if $\Delta m^2_{kj} = m^2_k - m^2_j$ and mixing angles are different from zero

$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta} \quad = \quad & \delta_{\alpha\beta} - 4 \sum_{k>j} \Re[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) \\
& + 2 \sum_{k>j} \Im[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)
\end{aligned}
$$

- Neutrino oscillations:
  - solar $\nu_e \to \nu_{\text{others}}$: $\theta_{12} \simeq 33^\circ$, $\Delta m^2_{12} \simeq 7.5 \times 10^{-5} \text{eV}^2$ (best fit)
  - atmospheric $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$: $\theta_{23} \simeq 40^\circ$ or 50°, $|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3} \text{eV}^2$ (best fit)
  - reactor $\bar{\nu}_e \to \bar{\nu}_{\text{others}}$: $\theta_{13} \simeq 8.7^\circ$ (best fit)
  - accelerator $\nu_\mu \to \nu_{\text{others}}$

Neutrino oscillations

- Oscillations $\Rightarrow$ Non-diagonal charged currents

$$\mathcal{L}_{\rm int} = -\frac{g}{\sqrt{2}} \boldsymbol{U_\nu^{ji}} \bar{\ell}_j \gamma^\mu P_L \nu_i W^-_\mu + \text{h.c.}$$

- 3 mass eigenstates $\nu_i = \nu_1, \nu_2, \nu_3$ different from the interaction eigenstates $\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$

$$\nu_\alpha = \boldsymbol{U_\nu^{\alpha i}} \nu_i$$

  $\Rightarrow$ $\boldsymbol{U_\nu}$ is a 3×3 unitary matrix, $U_\nu = U_{\rm PMNS}$

- $U_{\rm PMNS}$: 3 mixing angles + 1 CP violating phase (+ 2 Majorana phases)

- Oscillations give no information on:
    - the absolute mass scale
    - the Dirac or Majorana nature of neutrinos

Neutrino masses and nature

- Absolute masses
  - Tritium β decays: $m_{\nu_e} < 2.05$ eV [Kraus et al., 2005, Aseev et al., 2011]
  - Cosmology: CMB $\Sigma m_{\nu_i} < 0.98$ eV Planck: [Ade et al., 2013]
    CMB+BAO+H_0+flat Universe $\Sigma m_{\nu_i} < 0.23$ eV
- Hierarchy: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$?
  - Matter effect in the Sun: ν_1 is mostly ν_e
  - $\mathrm{sign}(\Delta m^2_{23})$? $\rightarrow$ matter effect in long baseline oscillations (T2K, NOνA, future projects)
- Neutrino nature (Dirac or Majorana):
  - Neutrinoless double β decay:
    $m_{2\beta} < 0.12 - 0.25$ eV KamLAND-ZEN: [Gando et al., 2013]

Massive neutrinos and New Physics

- Standard Model $L = \binom{\nu_L}{\ell_L}, H = \binom{H^+}{H^0}$
  - No right-handed neutrino $\nu_R \rightarrow$ No Dirac mass term

$$\mathcal{L}_{\text{mass}} = -Y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.}$$

  - No Higgs triplet $T \rightarrow$ No Majorana mass term

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} m \overline{L^C} T L + \text{h.c.}$$

- Necessary to go beyond the Standard Model for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\rightarrow \nu$ mass at tree-level
    + BAU through leptogenesis

Dirac neutrinos ?

- Add gauge singlet, right-handed neutrinos ν_R

$$\Rightarrow \nu = \nu_L + \nu_R$$

$$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R + \text{h.c.}$$

$\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = \binom{0}{\mathrm{v}}$

$$\mathcal{L}^{\text{leptons}}_{\text{mass}} = -\mathrm{v} Y_\ell \bar{\ell}_L \ell_R - \mathrm{v} Y_\nu \bar{\nu}_L \nu_R + \text{h.c.} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + \text{h.c.}$$

$\Rightarrow$ 3 light neutrinos: $m_\nu \lesssim 1\text{eV} \Rightarrow Y^\nu \lesssim 10^{-11}$

- Increase the hierarchy between Yukawa couplings

Majorana neutrinos ?

- Add gauge singlet, right-handed neutrinos ν_R
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R - \frac{1}{2} M_R \overline{\nu_R^C} \nu_R + \text{h.c.}$

  $\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = \binom{0}{\text{v}}$
  $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -m_\ell \ell_L \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2} M_R \overline{\nu_R^C} \nu_R + \text{h.c.}$

  $\Rightarrow$ 6 mass eigenstates: $\nu = \nu^C$

- ν_R gauge singlets
  $\Rightarrow$ M_R not related to SM dynamics, not protected by symmetries
  $\Rightarrow$ $M_R \overline{\nu_R^C} \nu_R$ is gauge and Lorentz invariant, renormalisable

- $M_R \overline{\nu_R^C} \nu_R$ violates lepton number conservation $\Delta L = 2$

The seesaw mechanism

- $\Delta L = 2, m_\nu \neq 0 \Rightarrow$ New physics
- Seesaw mechanism: New fields with a mass $M_R >$ EW scale (in general) and Majorana mass terms
  $\Rightarrow$ Generate m_ν in a renormalizable way and at tree-level
- Type I seesaw $\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R - \frac{1}{2} M_R \overline{\nu_R^C} \nu_R + \text{h.c.}$
  $\Rightarrow$ After EWSB, neutrino mass matrix $M_{6\times 6}^\nu$

$$M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^\intercal & m_R \end{pmatrix}$$

$m_D = \text{v} Y_\nu$ Dirac mass matrix
M_R Majorana mass matrix $\rightarrow \text{Diag}\{m_{R_i}\}$

$\Rightarrow$ Seesaw limit $M_R \gg m_D$

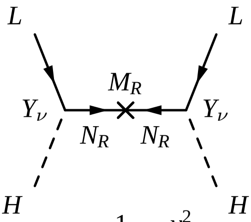
$$m_\nu^{\text{light}} \approx -m_D M_R^{-1} m_D^\intercal \qquad \nu^{\text{light}} \approx \nu_L + \nu_L^C$$

$$m_\nu^{\text{heavy}} \approx M_R \qquad \nu^{\text{heavy}} \approx \nu_R + \nu_R^C$$

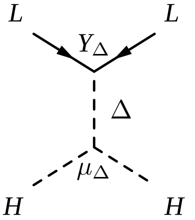
- Charged current matrix U_ν is 3×6
- 3 charged leptons + 3 light neutrinos: $\tilde{U}_{\text{PMNS}}$ = 3×3 submatrix of U_ν, maybe not unitary

Three seesaw mechanisms

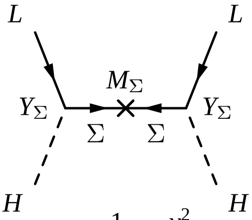
- Three minimal tree-level seesaw models ⇒ Three types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



$$m_\nu = -\frac{1}{2} Y_\nu^T \frac{v^2}{M_R} Y_\nu$$



$$m_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$



$$m_\nu = -\frac{1}{2} Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Effective approach to seesaw mechanisms

- Notice that lepton number conservation is accidental in the SM (gauge group, field content and renormalizability)
- Majorana ν cannot be associated to any global symmetry $\Rightarrow$ Effective non-renormalizable operators
- Unique dimension 5 operator for all seesaw mechanisms $\rightarrow$ Violates lepton number L $\Rightarrow$ Majorana neutrinos

$$\delta\mathcal{L}^{d=5} = \frac{1}{2} c_{ij} \frac{(\bar{L}_i \tilde{H})^\dagger (\bar{L}_j \tilde{H})}{\Lambda} + \text{h.c.}$$

- To distinguish the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, LC)
  - Look for dimension $\geqslant 6$ operator effects $\rightarrow$ charged lepton flavour violation (cLFV), non-standard interactions, etc

The inverse seesaw mechanism

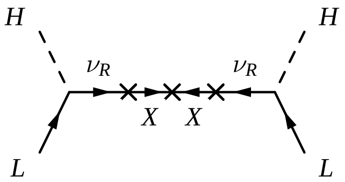
- Inverse seesaw $\Rightarrow$ Consider fermionic gauge singlets ν_{Ri} ($L=+1$, $i=1,2,3$) and X_i ($L=+1$, $i=1,2,3$)
  [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = Y_\nu^{ij}\overline{L_i}\tilde{H}\nu_{Rj} - M_R^{ij}\overline{\nu_{Ri}}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^C}X_j + \text{h.c.}$$

with $m_D = Y_\nu \mathrm{v}\,, M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$

$$m_\nu \approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2}$$

$$m_{1,2} \approx \mp\sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}$$



The inverse seesaw mechanism

- Type I seesaw: $M_R \simeq 10^{15}$GeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$
  or $M_R \sim 1$TeV with Yukawa $Y_\nu \sim \mathcal{O}(10^{-6})$
  $\Rightarrow$ Small active-sterile mixing $(\frac{m_D}{M_R}) \rightarrow \widetilde{U}_{\text{PMNS}} \sim U_{\text{PMNS}}$
  $\Rightarrow$ Small deviations from unitarity
- Inverse seesaw: $M_R \simeq 1$ TeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$
  $\Rightarrow$ Large active-sterile mixing $\rightarrow \widetilde{U}_{\text{PMNS}} \neq U_{\text{PMNS}}$
  $\Rightarrow$ Large deviations from unitarity ?
- Inverse seesaw: testable at the LHC and low energy experiments
  Could provide a sterile neutrino at the eV scale (reactor and LSND/MiniBooNE anomalies)

Lepton flavour universality

- Lepton flavour universality (LFU): gauge boson couplings are independent of lepton flavours
- Searches for LFU violation are among the most precise tests of the SM

$$\frac{\mathcal{B}(Z^0 \to \mu^+\mu^-)}{\mathcal{B}(Z^0 \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{\mathcal{B}(Z^0 \to \tau^+\tau^-)}{\mathcal{B}(Z^0 \to e^+e^-)} = 1.0019 \pm 0.0032$$

[Schael et al., 2006]

- Deviations from LFU $\Rightarrow$ Evidence of New Physics
- Could help disentangle different neutrino mass generation mechanisms
  - Magnitude of LFU violation
  - Correlation between different LFU tests

Lepton universality tests

- Couplings to different bosons can be tested: γ, Z^0, $W^\pm$

  Impact of singlet neutrinos ⇒ Focus on $W^\pm$ couplings

- Many observables can be used
  - Gauge boson decays (e.g. $W \to \ell\bar{\nu}$)
  - Leptonic and semileptonic meson decays (e.g. $K \to \ell\bar{\nu}$, $\overline{B} \to D\ell^-\bar{\nu}$)
  - Lepton decays (e.g. $\ell \to \ell' \nu\bar{\nu}$, $\tau \to K\nu$)

- We considered light meson decays: pions and kaons

  Decay width plagued by QCD uncertainties ⇒ Consider ratios

$$R_P = \frac{\Gamma(P^+ \to e^+\nu)}{\Gamma(P^+ \to \mu^+\nu)} \qquad P = K, \pi$$

Why R_K and R_π?

- Well measured by the NA62 collaboration [Lazzeroni et al., 2013]:

$$R_K^{\text{exp}} = (2.488 \pm 0.010) \times 10^{-5}$$

Current experimental error: $\frac{\delta R_K}{R_K} \simeq 0.4\%$
Expected sensitivity: $\frac{\delta R_K}{R_K} \simeq 0.1\%$

- SM prediction is very precise [Finkemeier, 1996, Cirigliano and Rosell, 2007]:

$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

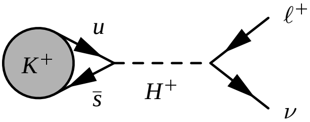
- New Physics: $R_K = R_K^{\text{SM}} (1 + \Delta r_K)$

$$\Delta r_K = (4 \pm 4) \times 10^{-3}$$

- Similar prospects for R_π

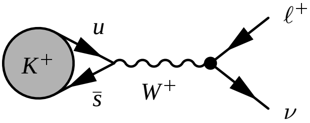
Deviations from the SM

- Origin of LFU violation in R_K:
  - New Lorentz structure in the four-fermion interaction



New fields, new couplings
e.g. 2 Higgs doublet models, Supersymmetry

  - Corrections to the SM $W\ell\nu$ vertex



New states, Higher-order effects
e.g. Additional neutrinos: low-scale seesaw, inverse seesaw

New Lorentz structure

- Two Higgs Doublet Model (2HDM) [Hou, 1993]

$$\Gamma^{\text{2HDM}}(K^+ \to \ell^+\nu) = \Gamma^{\text{SM}}(K^+ \to \ell^+\nu)\left(1 - \tan^2\beta \frac{m_K^2}{m_{H^+}^2}\frac{m_s}{m_s+m_u}\right)^2$$

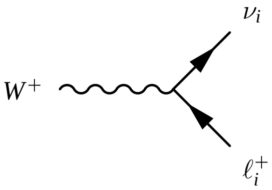
$\Rightarrow$ the tree-level correction is universal: $\Delta r_K^{\text{2HDM}} \sim 0$

- Supersymmetry
  - Tree-level correction is identical to 2HDM
    $\to$ higher-order corrections are required [Masiero et al., 2006]
  - In the unconstrained MSSM
    $\mathcal{B}(B \to \tau\nu)$ limits $\Delta r_K^{2HDM} < 10^{-3}$ [Fonseca et al., 2012]

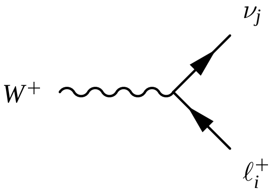
Modified $W\ell\nu$ vertex

- Naturally arises when leptonic mixing is added to the SM

SM: $gP_L\delta^{ij}$



SM + massive ν: $gP_L U_\nu^{ij}$



$$i = e, \mu, \tau; \quad j = 1, ..., n_\nu$$

- If $n_\nu = 3 \rightarrow U_\nu = U_{\rm PMNS}$, unitary
- If $n_\nu > 3$ (e.g. fermionic singlets) $\rightarrow U_\nu \neq U_{\rm PMNS}$
  $\rightarrow U_\nu$ is a $3 \times n_\nu$ non-unitary matrix
  $\rightarrow \tilde{U}_{\rm PMNS}$ is not unitary
- Tree-level corrections to R_K

Deviation from universality

- Summing over all the kinematically accessible neutrinos (from 1 to $N^{(e)}_{\text{max}}$, $N^{(\mu)}_{\text{max}}$ the heaviest kinematically allowed neutrino) :

$$R_K = \frac{\sum_{i=1}^{N^{(e)}_{\text{max}}} |U_\nu^{1i}|^2 G^{i1}}{\sum_{k=1}^{N^{(\mu)}_{\text{max}}} |U_\nu^{2k}|^2 G^{k2}} \quad \text{with}$$

$$G^{ij} = \left[m_K^2(m_{\nu_i}^2 + m_{l_j}^2) - (m_{\nu_i}^2 - m_{l_j}^2)^2\right]\left[(m_K^2 - m_{l_j}^2 - m_{\nu_i}^2)^2 - 4m_{l_j}^2 m_{\nu_i}^2\right]^{1/2}$$

- In the SM + 3 massive ν, one recovers $R_K^{SM} = \frac{m_e^2}{m_\mu^2}\frac{(m_K^2-m_e^2)^2}{(m_K^2-m_\mu^2)^2}$
  - $m_\nu \ll m_\ell \Rightarrow G^{i1} = G^{j1}$
  - $U_\nu = U_{\text{PMNS}} \Rightarrow \sum_{i=1}^{n_\nu} |U_\nu^{1i}|^2 = (U_\nu U_\nu^\dagger)_{11} = 1$

- 2 ways to deviate from universality:
  - (A) sterile neutrinos are lighter than m_K, with $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$
    $\rightarrow$ Phase space effect
  - (B) sterile neutrinos are heavier than the kaon, $m_{\nu_s} > m_K$
    $\rightarrow \tilde{U}_{\text{PMNS}}$ is not unitary

Is there a visible deviation from LFU ?

- Yes!

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- Effect of deviation from unitarity [Shrock, 1980, 1981]
- However, current experimental constraints on sterile neutrinos and non-unitary are quite stringent

Constraints on sterile neutrinos

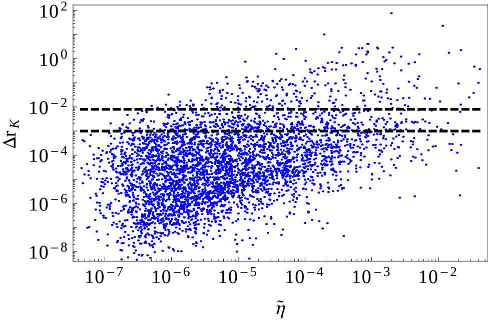
- Depend on the mass regime and the size of active-sterile mixing
  - Direct searches (e.g. monochromatic lines in $\pi \to \mu\nu$): [Atre et al., 2009, Kusenko, 2009]
  - Non-unitarity constraint $\widetilde{U}_{\mathrm{PMNS}} = (\mathbb{1} - \eta)U_{\mathrm{PMNS}}$: [Antusch et al., 2009]
  - Lepton flavour violation (e.g. $\mu \to e\gamma$): [Deppisch and Valle, 2005]
  - B Physics (e.g. $B \to \ell\nu$)

Constraints on sterile neutrinos

- Depend on the mass regime and the size of active-sterile mixing
  - LHC Higgs searches (e.g. invisible decays): [Bhupal Dev et al., 2012, Cely et al., 2013]
  - Electroweak precision data: [del Aguila et al., 2008, Atre et al., 2009]
  - Cosmological observations (e.g. LSS, Lyman-α, CMB, BBN, X-ray): [Smirnov and Zukanovich Funchal, 2006, Kusenko, 2009] $\rightarrow$ can be evaded with non-standard cosmology (*e.g.* low reheating temperature [Gelmini et al., 2008])

R_K in the inverse seesaw

- Inverse seesaw as an illustrative example, only one among other possibilities
- Numerical results in scenario (A): $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$



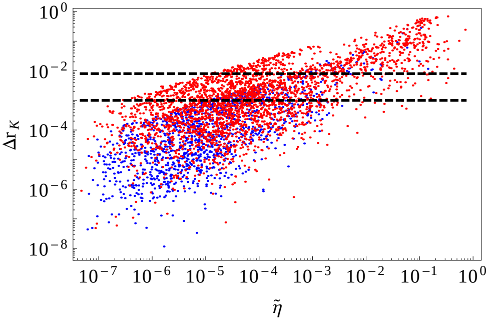
$M_R \in [0.1\text{ MeV}, 200\text{ MeV}]$
$\mu_X \in [0.01\text{ eV}, 1\text{ MeV}]$

$\tilde{\eta} = 1 - \left|\text{Det}(\tilde{U}_{\text{PMNS}})\right|$

- Comply with all constraints, except cosmological bounds
- Large LFU violation $\Delta r_K \sim 1$ can be reached
- Small $Y_\nu \to$ no cLFV signal expected

R_K in the inverse seesaw

- Numerical results in scenario (B): $m_{\nu_s} > m_K$



$M_R \in [1 \text{ GeV}, 10^6 \text{ GeV}]$
$\mu_X \in [0.01 \text{ eV}, 1 \text{ MeV}]$
$Y_\nu > 10^{-2}$ $Y_\nu < 10^{-2}$

$\tilde{\eta} = 1 - |\text{Det}(\tilde{U}_{\text{PMNS}})|$

- Comply with all constraints, even the stringent non-unitarity bounds
- Large LFU violation $\Delta r_K \sim 1$ can be reached
- Large $Y_\nu \to \mathcal{B}(\mu \to e\gamma)$ is within MEG reach
- Specific to the inverse seesaw with its large active-sterile mixing

R_K summary

- Source: modified $W\ell\nu$ vertex from extra sterile neutrinos
- Mechanism: phase space effect for $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$
  non-unitarity of $\widetilde{U}_{\text{PMNS}}$ for $m_{\nu_s} > m_K$
- Results: large LFU violation ($\Delta r_K \lesssim 1$) in the inverse seesaw
- Similar results for R_π

Other observables

- Leptonic $W^{\pm}$ decays

$$R^{W}_{\tau\ell} = \frac{2\mathcal{B}(W \to \tau\bar{\nu}_\tau)}{\mathcal{B}(W \to \mu\bar{\nu}_\mu) + \mathcal{B}(W \to e\bar{\nu}_e)} = 1.077 \pm 0.026$$

$\Rightarrow$ 2.8σ deviation from the SM prediction $R^{W}_{\tau\ell}|_{SM} = 0.999$
[LEP, 2005, Kniehl et al., 2000]

- Other leptonic meson decays

$$R_{D_s} = \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} \simeq 9.2$$

$\Rightarrow$ roughly 1σ away from the SM prediction $R_{D_S}|_{SM} \simeq 10.1$
[Beringer et al., 2012, Charles et al., 2011]

Other observables

- Semileptonic τ decays

$$R^{\tau}_{K,\mu} = \frac{\mathcal{B}(\tau^- \to K^- \nu)}{\mathcal{B}(K^+ \to \mu^+ \nu)} \simeq 469$$

$\Rightarrow$ within 1σ of the SM prediction $R_{K,\mu}|_{SM} \simeq 474$ [Beringer et al., 2012]

- Semileptonic meson decays

$$R(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^- \bar{\nu}_\ell)} = 0.440 \pm 0.072$$

$\Rightarrow$ deviates by 1.7σ from the SM prediction $R(D)|_{SM} = 0.31 \pm 0.02$
[Lees et al., 2012, Becirevic et al., 2012]

Other observables

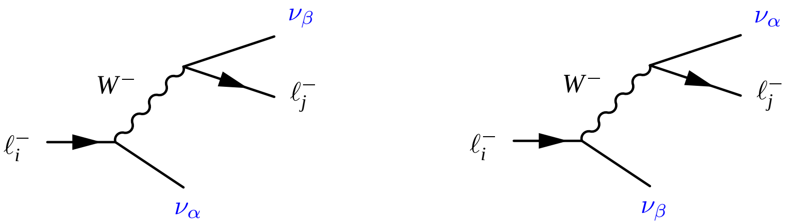
- 3-body lepton decays: $\ell_i \to \ell_j \nu\nu$
- Test LFU via ratios, e.g.

$$R_\tau = \frac{\Gamma(\tau^- \to \mu^- \nu\nu)}{\Gamma(\tau^- \to e^- \nu\nu)} = 0.9764 \pm 0.0030$$

$\Rightarrow$ within 2σ of the SM prediction $R_\tau|_{SM} \simeq 0.9726$ [Beringer et al., 2012]

- 2 massive neutrinos in the final state
  $\rightarrow$ Sensitive to the Majorana or Dirac nature of the neutrino

Other observables



- $\Gamma_{\text{Majorana}} = \Gamma_{\text{Dirac}} + \Gamma_{\text{interferences}}$

$$\Gamma_{\text{interferences}} \propto \Re(U^*_{i\alpha} U_{j\beta} U_{i\beta} U^*_{j\alpha}) \frac{m_{\nu_\alpha} m_{\nu_\beta}}{m^2_{\ell_i}}$$

- Large active-sterile mixing + heavy sterile neutrinos ($m_{\nu_s} \sim \mathcal{O}(m_{\ell_i})$) $\Rightarrow$ Potentially sizeable deviations (under investigation)

Conclusion

- Lepton universality tests: good theoretical precision and experimental prospects
- Sterile neutrinos can lead to a large violation of LFU at tree-level
- R_K particularly well-suited for this search
- Large deviations from the SM can be found
- Can appear in other observables with leptonic charged currents
  $\rightarrow$ Currently under investigation

Backup slides

Leptogenesis

- Generate the baryonic (leptonic) asymmetry → Sakharov conditions [Sakharov, 1967]
  - Out of equilibrium process
  - Baryon (lepton) number violation
  - C and CP violation
- Impossible in the Standard Model: not enough CP violation [Gavela et al., 1994]
- Use the leptonic sector
  - Majorana mass term violates lepton number conservation ⇒ Passed to the baryonic sector via sphalerons ($B - L$ conserving)
  - Neutrinos mass matrix ⇒ Extra sources of CP violation ($\delta_{13}, \alpha_{1,2}$)

Scan method

- Inverse seesaw as an illustrative example, only one among other possibilities
- Random scan on M_R and μ_X entries
- Y_ν obtained from neutrino data via the Casas-Ibarra parametrization [Casas and Ibarra, 2001]

$$Y_\nu^T = \frac{\sqrt{2}}{v} V^\dagger \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})\, R\, \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) U_{PMNS}^\dagger$$

  where R is a complex orthogonal matrix and V a unitary matrix that decompose $M = M_R \mu_X^{-1} M_R^T$ according to $M = V^\dagger \mathrm{diag}(M_1, M_2, M_3) V^*$.

- Apply the constrains